

Australian coal mine methane emissions mitigation potential using a Stirling engine-based CHP system



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HIGHLIGHTS

- We study the application of Stirling engines in coal mine CHP systems.
- We develop a thermo-economic approach based on the net present worth analysis.
- We examine the impact of a carbon tax and ETS on the economics of the system.
- The modeled system leads to a substantial reduction in greenhouse gas emissions.
- Carbon tax provides a greater incentive to address the methane emissions.

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ABSTRACT

Methane, a major contributor to global warming, is a greenhouse gas emitted from coal mines. Abundance of coal mines and consequently a considerable amount of methane emission requires drastic measures to mitigate harmful effects of coal mining on the environment. One of the commonly adopted methods is to use emitted methane to fuel power generation systems; however, instability of fuel sources hinders the development of systems using conventional prime movers. To address this, application of Stirling engines may be considered.

Here, we develop a techno-economic methodology for conducting an optimisation-based feasibility study on the application of Stirling engines as the prime movers of coal mine CHP systems from an economic and an environmental point of view. To examine the impact of environmental policies on the economics of the system, the two commonly implemented ones (i.e. a carbon tax and emissions trading scheme) are considered. The methodology was applied to a local coal mine. The results indicate that incorporating the modelled system not only leads to a substantial reduction in greenhouse gas emissions, but also to improved economics. Further, due to the heavy economic burden, the carbon tax scheme creates great incentive for coal mine industry to address the methane emissions.

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1. Introduction

Australia enjoys abundant coal reserves. Black coal (sub-bituminous, bituminous, and anthracite) and brown coal (also referred to as lignite) are the two forms of coal mined in Australia. Australian black coal resources account for 10.6% and the brown coal resources account for 8.9% of the world total reserves and considering the current rate of consumption their reserves are expected to last for 111 years and 539 years, respectively (Department of Resources, Energy, and Tourism, 2011). Due to its abundance, coal is a relatively cheap fuel and the vast majority of Australian electricity is generated using

black or brown coal. Further, coal constitutes a large proportion of country's exports.

Formation of coal through compression and heating of organic materials, results in generation of methane entrapped in fissures and pores of coal beds. Coal Mine Methane (CMM), which is released during active coal mining, typically has a methane content of 25% to 60% (Evans, 2007). The greenhouse effect of one tonne of methane is nearly twenty-one times that of one tonne of carbon dioxide (The NSW Greenhouse Gas Reduction Scheme, 2005) and although its atmospheric presence is insignificant (compared to that of carbon dioxide), after several years it breaks down into water and CO₂. It is predicted that CMM emissions will exceed 500 Mt CO₂-e by 2015 (Talkington, 2010). Therefore, to reduce the emissions of methane, coal mining industry needs to take drastic measures.

Using CMM in power generation systems not only reduces methane emissions but also provides a cheap fuel and therefore

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Nomenclature

AFEM	avoided fugitive methane through the use of CMM (t CO ₂ -e)
C	cost (\$/kW h)
CC	capital cost (\$)
CF	combustion factor
CHP	combined heat and power
COF	cost of fuel per hour (\$/h)
CONF	conversion factor (kt/GJ)
EF	emission factor (kt/GJ)
EM	emissions (t CO ₂ -e)
ET	the emissions term
FEF	fugitive emission factor (t CH ₄ /t coal)
FEM	fugitive methane associated with the production of coal (t CO ₂ -e)
$\dot{H}$	heat rate (kW)
i	interest rate (%)
K	number of equipment
LT	lifetime (year)
MC	maintenance cost per hour (\$/h)
n	payback period (year)
N	number of time intervals of demand profile
NAP	net annual profit (\$/year)

NPW	net present worth (\$)
P	electric power (kW)
PL	partial load (%)
PWB	present worth of benefits (\$)
PWC	present worth of cost (\$)
SV	salvage value (\$)

Greek symbols

η	efficiency (%)
τ_m	time interval of demand profile (h)

Subscripts

b	buying electricity
CHP	combined heat and power
el	electricity
h	heat
Nom	nominal
PL	partial load
r	required
s	selling electricity
th	thermal

has proved to be a viable option. However, instability of CMM sources (i.e. inconsistency of methane concentration and pressure) adversely affects the development of power generation systems using conventional prime movers (e.g. gas engine and gas turbine) which are unable to satisfactorily accommodate instability in fuel sources (Bao-sheng et al., 2009). Stirling engine is an external combustion engine and its working fluid is not involved in the combustion process. External combustion allows for better capability to deal with fuel instability as well as complete combustion and consequently minimising the production of carbon monoxide. Therefore, a Stirling engine-based system can be considered as a potential alternative to the conventional power generation systems. In addition, using porous media burners has been proposed to enhance system's capability for dealing with the fuel instability (Bao-sheng et al., 2009; Fan et al., 2011).

In spite of being an old engine concept, Stirling engine is still an emerging technology and consequently published research papers on large scale Stirling engine-based CHP systems are scarce. However, application of Stirling engines in micro scale CHP systems has recently intrigued researchers. For example, Rogdakis et al. (2012) installed a Solo V161 Stirling engine-based CHP system and conducted a thermodynamic analysis of the system by developing a specially designed computer code (based on a Stirling engine adiabatic thermodynamic analysis model) as well as performing a thermal balance study of the unit. They also conducted an experimental assessment of the system under different working conditions (i.e. various working pressures, output powers, and heat load stages). The results indicated that the studied system is a viable option for micro CHP applications and comparable with systems with other types of prime movers. Magri et al. (2012) analysed the economic and energetic performance of a cogenerative gas boiler which consisted of a Stirling engine and a condensing heat exchanger with an electric output of 1 kW. As a case study, they studied a unit installed in a detached house in Milan, Italy, and considered a condensing gas boiler as the reference case. Three heating schedules were adopted. Results led to the conclusion that installing the CHP systems results in primary energy demand and greenhouse gas emissions reduction

as well as economic benefits. However, this varies with the heating schedule followed.

Alanne et al. (2010) by considering hydronic heating and a low temperature gas boiler as the reference system, studied the optimum strategy of incorporating a Stirling engine-based CHP system to residential buildings (standard and passive constructions) located in various climatic regions. They modelled the system using the simulation program commonly used in Nordic countries, where the Stirling engine routine is implemented following the model specifications of Annex 42 of the International Energy Agency's energy conservation in buildings and community systems program. Their findings implied that a reduction of 3–5% in primary energy consumption and CO₂ emissions as well as annual savings would be achieved as a result of the optimally operated system. Aliabadi et al. (2009) conducted an experimental analysis of a residential Stirling engine-based CHP system operated on both diesel and biodiesel fuels comparing efficiencies as well as the emissions. The efficiencies (i.e. power efficiency and heat efficiency) of the system ran on diesel were slightly higher. The total unburnt hydrocarbon emissions for biodiesel were higher than those of diesel. Particulate emissions for biodiesel were significantly higher but emissions of carbon monoxide, nitrogen dioxide, methane, acetylene, ethylene, formaldehyde, and acetaldehyde were comparable. Nitric oxide emissions were the sole case for which diesel fuel caused higher amounts. Further, efficiencies of the system proved to be comparable with internal combustion engine-based and fuel cell-based CHP systems. There have also been several attempts to study micro CHP systems with Stirling engine as the prime mover which operate on unconventional fuels (wood pellet, waste gas, etc.) from a technical, an environmental, and a techno-economic point of view (Li et al., 2012; Alanne et al., 2012; Obara et al., 2009; Nishiyama et al., 2007).

There are also several studies on coal mine gas extraction techniques as well as its utilization methods in the context of greenhouse gas emissions mitigation, safety hazards reduction, and economic profitability (Wang and Cheng, 2012; Ruiz et al., 2012; Li and Xu, 2009; Huang et al., 2011), e.g. Wang et al. (2012) studied longhole directional drilling technology as a method to significantly reduce greenhouse gas emissions from coal mines.

As a novel method of utilizing this source of energy, Groß et al. (2011) studied the use of coal mine gas as a fuel for a solid oxide fuel cell. The available technology was modified to operate on the new fuel and a test facility was designed to run a fuel cell stack with a specially designed pre-reformer. A series of tests were conducted which indicated the feasibility of this new application. Brinkmann et al. (2008) studied gas permeation process as a method of increasing the methane content of coal mine gas to be used as a feed stock for high-temperature fuel cells. Their analysis proved the viability of the adopted method.

In our study, we aim to conduct an optimization-based feasibility analysis of a Stirling engine-based combined heat and power system installed at a coal mine. We examine the CHP system from a techno-economic as well as an environmental point of view. This is, to the best of our knowledge, the first attempt to develop a techno-economic approach to optimally size CMM fuelled Stirling engines as the prime movers of coal mine CHP systems. We have also studied the impact of the two commonly adopted measures to deal with greenhouse gas emissions (i.e. emissions trading scheme and a carbon tax) on the economics of the system. We have conducted a comprehensive sensitivity analysis determining the extent to which results are affected by changes in these schemes.

To account for the possible connection methods to the grid, two operational modes have been considered; namely, one-way connection mode (OWC) and two-way connection mode (TWC). For OWC mode, it is only allowed to purchase electricity from the grid (i.e. grid acts as a backup source of electricity to offset the shortfall in generation) while in TWC it is also possible to sell the surplus produced electricity to the grid.

2. System description

Stirling engine is an external combustion engine which operates on a closed regenerative thermodynamic cycle. With Stirling cycle, compression and expansion occur at different temperature levels (i.e. isothermal compression and expansion) and heat addition and rejection are constant volume processes. External combustion allows the use of a wide variety of fuels, including renewable energy sources (e.g. biomass and solar). Due to the continuous combustion process, two power pulses per revolution, and fewer moving parts, Stirling engines enjoy low wear, long maintenance intervals as well as a quieter and smoother operation in comparison with reciprocating internal combustion engines (Onovwion and Ugursal, 2006). In addition, their emissions are relatively low (Thombare and Verma, 2008).

Stirling engines are classified into two main categories: kinematic and free piston. With kinematic Stirling engines, pistons are connected by rods and a crankshaft while in free piston design there is no mechanical coupling between the piston and the power output. The free piston configuration is limited to small sizes of up to 12.5 kW (ASHRAE, 2008); however, feasible capacities of the common design are within the range of about 3 kW to 1.5 MW (Austrian Energy Agency, 2006; EDUCOGEN (The European Educational Tool on Cogeneration), 2001). Energy balance for a typical Stirling engine is such that the thermal efficiency, the coolant energy content, and the exhaust energy content are 30%, 50%, and 20%, respectively (ASHRAE, 2008; NREL (National Renewable Energy Laboratory), 2003). Further, as an important parameter in the context of combined heat and power applications, heat-to-power ratio [i.e. the proportion of useful heat (e.g. in the form of hot water) to power produced in the CHP system] ranges from 1.2 to 1.7 (Al-Sulaiman et al., 2011).

There is a lack of data on partial load performance of Stirling engines and studies on off-design performance are scarce. The following equation, obtained from a theoretical model presented

by Smith (2002), which is consistent with the test results of an engine provided by Kuhn et al. (2008) (maximum difference of 9%), estimates the relative efficiency (%) of Stirling engine in terms of partial load (%):

$$\frac{\eta_{th,PL}}{\eta_{th,Nom}} = 0.0001481(PL)^3 - 0.03289(PL)^2 + 2.566(PL) + 24.66 \quad (1)$$

Eq. (2), obtained from the operational data presented by Kuhn et al. (2008), is proposed to estimate the relative total heat available for CHP applications (%):

$$\frac{\dot{H}_{PL}}{\dot{H}_{Nom}} = 1.75(PL)^{0.8768} \quad (2)$$

Working at off-design conditions does not lead to a dramatic decline in Stirling engine efficiency and consequently its partial load performance is satisfactory; however, the engine's response to load variations is relatively slow and a rapid change to another power output level is difficult to achieve (Chamra and Mago, 2009). In addition, currently most manufacturers design their engines for base load operation. Therefore, in this study the base load application of Stirling engine (i.e. nominal power performance) is considered.

Drying of coal is of paramount importance to increase its calorific value and facilitate its transport. In the modelled Stirling engine-based CHP system, the recovered heat from the exhaust and coolant of the prime mover is utilized to preheat the air entering the dryer. The considered dryer is a specific type of fluidized bed dryers which is, due to the simple design and high capacity, commonly used for coal drying (Mujumdar, 2006). The dryer's heat consumption is typically considered to be 3550 kJ/kg of removed H₂O (Mujumdar, 2006) and the electrical energy required for drying one tonne of coal is estimated to be 5.8 kW h (EPA (United States Environmental Protection Agency), 1998). If the supplied heat by the CHP system is not sufficient to meet the thermal demand, coal will be used as the supplementary source of energy.

Due to low heat transfer coefficients of air (as the fluid to recover heat) and the exhaust gases as well as the need for a high effectiveness to make the CHP system more economically favourable, extended surface heat exchangers are considered. A plate-fin heat exchanger and a tube-fin heat exchanger are utilized to recover heat from the exhaust gases and the engine coolant, respectively. The effectiveness of the heat exchangers is assumed to be 80% (Shah and Sekulic, 2003). Also, the generator is considered to be 97% efficient (Aghaei Meybodi and Behnia, 2011). It should be noted that in this paper we primarily focus on the sizing of the prime mover and a detailed analysis of other components are beyond the scope of this study. Fig. 1 illustrates the schematic diagram of the system considered here.

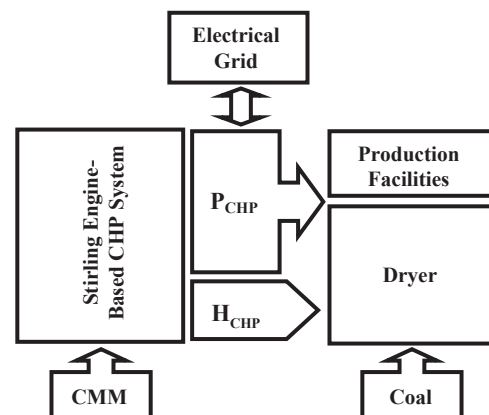


Fig. 1. Schematic diagram of the modelled CHP system.

3. Methodology

3.1. Modelling greenhouse gas emissions

Emissions of greenhouse gases are commonly expressed in tonnes of CO₂ equivalent (t CO₂-e). In this study, emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are considered. To estimate the amount of emitted greenhouse gases, based on the type of fuel used and its consumption, the relations provided by the New South Wales Greenhouse Gas Reduction Scheme (GGAS), which is one of the first greenhouse gas emissions trading schemes (ETS) in the world, are used. It is noted that due to an ongoing debate and intense disagreement, Australia's long term plan to deal with the environmental issues associated with the fossil fuel consumption suffer from considerable uncertainties; however, as an interim measure the federal government has introduced a carbon tax. To conduct a comprehensive study, impacts of both ETS and a carbon tax on the economics of the system is examined here.

Although under both policies the same set of relations are used to calculate the emissions, the methodology for estimating the cost incurred or profit earned is different. The following equations are proposed to estimate the amount of greenhouse gasses emitted on the basis of fuel consumed (The NSW Greenhouse Gas Reduction Scheme, 2005):

$$EM_{CO_2} = \text{energy content of fuel} \times EF_{CO_2} \times CF \times 1000 \quad (3)$$

$$EM_{CH_4} = \text{energy content of fuel} \times EF_{CH_4} \times 1000 \times 21 \quad (4)$$

$$EM_{N_2O} = \text{energy content of fuel} \times EF_{N_2O} \times 1000 \times 310 \quad (5)$$

$$FEM_{CH_4} = \text{mass of coal} \times FEF_{CH_4} \times 21 \quad (6)$$

$$AFEM_{CH_4} = \text{energy content of waste methane used as fuel} \times CONF_{CH_4} \times 1000 \times 21 \quad (7)$$

Table 1 lists the values considered for the above factors in this study (The NSW Greenhouse Gas Reduction Scheme, 2005). Further, the weighted state average for FEF_{CH_4} is 0.00367 t CH₄/t coal and $CONF_{CH_4}$ is 18×10^{-6} kt CH₄/GJ. It is noteworthy that for obtaining the values in Table 1 for coal mine gas and black coal, their application (i.e. as fuel for Stirling engine and dryer) has also been considered.

Under GGAS, participants can create tradable NSW Greenhouse Abatement Certificates (NGAC), their compliance with a specified benchmark is measured, and are able to buy the required certificates to satisfy the compliance criteria from the accredited providers or sell the excess NGACs for a profit. With the carbon tax policy, annual total emissions are calculated and taxed at a certain rate.

3.2. Present worth analysis

As a commonly applied method of analysing engineering projects from an economic point of view, present worth approach is adopted here. Net Present Worth (NPW), which is the decisive

criterion in this method, is obtained by deduction of Present Worth of Cost (PWC) from Present Worth of Benefits (PWB). Positive NPW values imply that the project is economical. In addition, the maximum value indicates the optimum option. The proposed objective function (NPW \$), which thoroughly accounts for the economic parameters (e.g. capital cost, maintenance cost, etc.) as well as performance characteristics of the CHP system, is defined as (Newnan et al., 2004; Aghaei Meybodi and Behnia, 2012):

$$NPW = \sum_{j=1}^k \left(SV_j \left(\frac{1}{(1+i)^{LT}} \right) - CC_j \right) - \left(\frac{(1+i)^{LT}-1}{i(1+i)^{LT}} \right) \left[ET + \sum_{m=1}^N \left[\sum_{j=1}^k (MC_j + COF_j) + P_b \times C_{el,b} - P_{CHP,r} \times C_{el} - \dot{H}_{CHP,r} \times C_h - P_{CHP,s} \times C_{el,s} \right] \times \tau_m \right] \quad (8)$$

The emissions term (ET) in Eq. (8), is either the annual carbon tax with the carbon tax scheme, or the annual cost (or profit) under the emissions trading scheme. In addition to NPW, payback period provides another means of economically evaluating the CHP system; payback period values which exceed the system lifetime correspond to uneconomical options. To estimate the payback period, the following equation is solved for n (Aghaei Meybodi and Behnia, 2012):

$$NPW \left(\frac{(1+i)^n-1}{i(1+i)^n} \right) + \sum_{j=1}^k SV_j \left(\frac{1}{(1+i)^n} \right) = \sum_{j=1}^k CC_j \quad (9)$$

The actual values of capital and maintenance cost of the equipment should be provided by the manufacturers; however, due to the commercial considerations the exact market values are hard to obtain. To address this issue, we use openly published data, which provides a reasonable estimate. For the capital cost of a Stirling engine (including the generator) per unit of nominal capacity the value of 2900 \$/kW_{el} (Sanchez et al., 2009) is proposed and for the maintenance cost a figure of 0.078 \$/kW_{el}h is adopted (Sanchez et al., 2009; Shaneb et al., 2011).

The dryer's capital cost is considered to be \$117,000 per each tonne per hour of capacity (Osman et al., 2011) and the value of \$0.4 per each tonne of dried coal is assumed for the maintenance cost (Osman et al., 2011; EPA (United States Environmental Protection Agency), 2006). The capital cost of heat exchangers per unit of recovered heat rate is estimated to be 60 \$/kW_{th} and 160 \$/kW_{th} for the plate-fin and the tube-fin heat exchangers, respectively (Traverso and Massardo, 2005; Raghupatruni et al., 2007). Further, the system lifetime, the salvage value, and the nominal interest rate are considered to be 15 years (Shaneb et al., 2011), 10%, and 6%, respectively.

3.3. Optimisation of nominal power

The following procedure is adopted to optimally determine the nominal capacity of the Stirling engine-based combined heat and power system. It is based on the assumption that, as noted before, the CHP system supplies the based load and the shortfall is purchased from the grid. Further, in order to avoid exceeding the maximum feasible nominal power of Stirling engine, if supplying the total capacity requires so, the system may consist of a number of Stirling engines with each prime mover supplying an equal share of the total load (i.e. engines are identical and nominal power is the same for all of them).

For the CHP system nominal capacities from 100 kW (lower limit is flexible and has been chosen for mining application) to 1 MW (the upper limit in the first iteration) and for each time

Table 1
The factors considered for calculating the emissions.

Factor	Black coal	Coal mine gas
CF	0.99	0.995
EF_{CO_2} (kt CO ₂ /GJ)	93×10^{-6}	508×10^{-7}
EF_{CH_4} (kt CH ₄ /GJ)	13×10^{-10}	1×10^{-10}
EF_{N_2O} (kt N ₂ O/GJ)	8×10^{-10}	1×10^{-10}

interval of demand profile (τ_m) calculating NPW (which is represented by NPW_m).

1. Adding up the NPW_m values for all time intervals to calculate NPW.
2. If the maximum value of NPW (NPW_{max}) corresponds to the upper limit of the CHP system nominal capacity range, the range is increased by an increment of 1 MW (e.g. for the second iteration the range of nominal capacities is 100 kW to 2 MW) and steps 1 and 2 are repeated. This process continues until a nominal capacity within the considered range (and below the upper limit) leads to the maximum NPW value.
3. The nominal capacity associated with the maximum net present worth value is the optimum nominal capacity of the CHP system (which is designated by $P_{CHP,opt}$). The nominal power of each Stirling engine is the optimum system capacity divided by the number of units.
4. For all time intervals, the operational strategy of the system is working at $P_{CHP,opt}$.

The proposed methodology is versatile and can be applied to any size of CHP system as well as any number of prime movers. It can also be further developed to take the off-design performance of Stirling engines into account.

4. The case study

To demonstrate the application of the proposed methodology we have chosen a case study here. The analysis is carried out for Dendrobium Mine located south of Sydney, New South Wales, Australia. The mine is an underground coal mine at which mining started in April 2005. The mine operates on a continuous basis, 24 h a day and seven days a week. Dendrobium mine produces coking coal and is approved to produce up to 5.2 million tonnes per annum. The service life of the mine is expected to be 20 years (Dendrobium Coal Pty Ltd, 2009a).

There is no on-site power generation facility and the mine purchases the required electricity. Furthermore, as the produced coking coal is relatively high in quality with a low moisture content of around 8% (Dendrobium Coal Pty Ltd, 2009b; Railpage Australia, 1996) drying is not crucial and there is no dryer on-site. However, as drying coking coal reduces the coking time and increases coke oven productivity by about 10–15% (Mujumdar, 2006; Jackman and Helfinstine, 1970; Burmistrz et al., 2005) the use of dryer for the mine is feasible. Excessive drying adversely affects the coking properties of coal and therefore to avoid this, the final moisture content of 4% is selected (Jackman and Helfinstine, 1970; Burmistrz et al., 2005).

Fig. 2 shows the estimated monthly electricity and heat demand profile for the case study. The electricity demand comprises the mine production facilities demand to produce 3 million tonnes of coking coal for FY09 (Dendrobium Coal Pty Ltd, 2009a) as well as the demand associated with the drying process and the heat demand is the dryer's heat consumption. In addition, by applying Eq. (6) the monthly methane production and consequently the available energy can be estimated; as depicted in Fig. 3. The cost of electricity and coking coal as well as the value of generated heat and electricity are listed in Table 2 (Hernandez, 2012; Origin energy, 2012).

Under both environmental policies the equations provided in Section 3.1 are used to estimate the total emissions (in terms of t CO₂-e). With the carbon tax scheme, the total emissions are taxed at a certain rate. In this study, a nominal carbon tax of \$23 per emitted tonne of CO₂ equivalent (the starting rate imposed by the Australian government) is considered. Under the ETS scheme

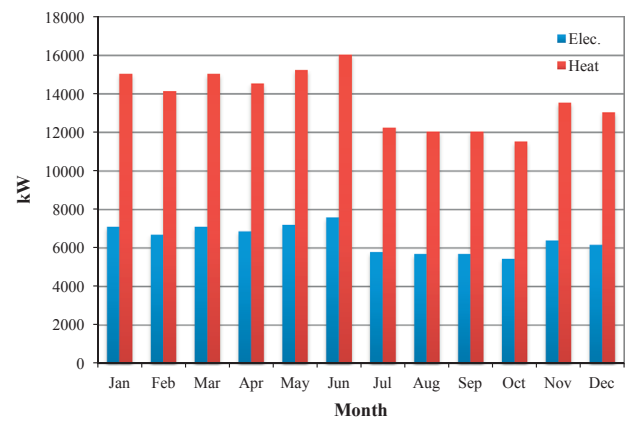


Fig. 2. The monthly demand profile.

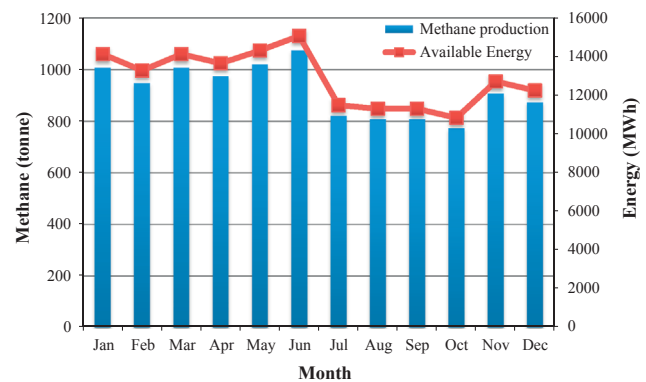


Fig. 3. Monthly methane emissions and the available energy.

Table 2

The energy price list of the case study.

Items	Price
Buying electricity ($C_{el,b}$)	0.215 \$/kW h
Selling electricity ($C_{el,s}$)	0.185 \$/kW h
Generated electricity (C_{el})	0.215 \$/kW h
Generated heat (C_h)	0.028 \$/kW h
Coking coal	0.226 \$/kg

(i.e. New South Wales Greenhouse Gas Reduction Scheme) the methodology provided by the Generation and the Demand Side Abatement Rules is used to determine the number of NGACs that may be created. If the CHP system satisfies the compliance criteria obtained by the methodology stated by the Compliance rule, the excess NGACs are sold for a profit; otherwise the required NGACs are purchased from the market to offset the shortfall. It is noted that further elaboration of the scheme is beyond the scope of this paper. As for NGAC price, a nominal value of \$4.25 per emitted tonne of CO₂ equivalent [the average NGAC spot price in year 2011 (Nextgen, 2012)] is used.

5. Results and discussion

Fig. 4 shows the variation of NPW versus the Stirling engine-based CHP system nominal power for TWC mode of operation. As shown, nominal system capacities of 6700 kW with the payback period of 6 years and 6300 kW with the payback period of 8.1 years have led to the maximum NPW values under the carbon tax and ETS schemes, respectively. The carbon tax curve has a steeper slope compared to

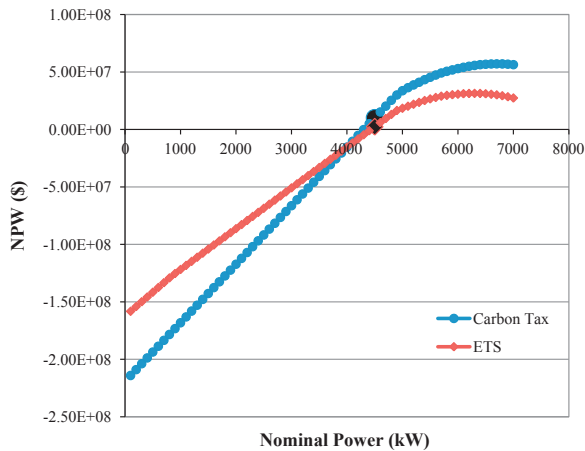


Fig. 4. Variation of NPW versus CHP system nominal power in TWC mode of operation.

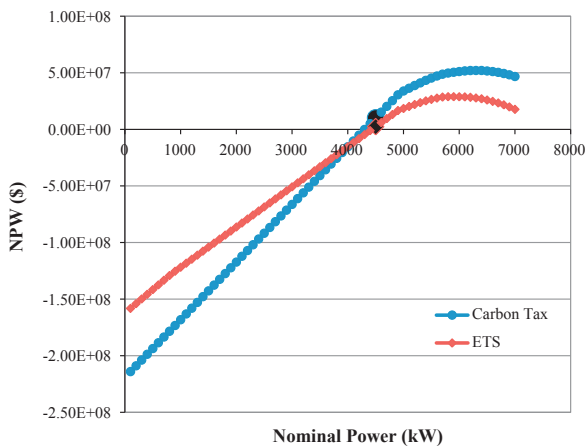


Fig. 5. Variation of NPW versus CHP system nominal power in OWC mode of operation.

that of the ETS curve. This is due to the fact that the carbon tax scheme has a considerably greater impact on the economics of the system. Under the carbon tax scheme, the penalty applied to the mine for emitting methane is significantly heavier in comparison with the cost incurred as a result of failing to comply with the determined benchmark with ETS scheme, in which the required abatement certificates to meet the benchmark can be purchased from the market. Therefore, at low nominal powers, carbon tax results in a substantially lower NPW value. As nominal power increases, more methane is used and the CHP system makes a profit (relative to the mine without a CHP system as the reference case) either by paying less tax under the carbon tax scheme or through buying less certificate (the system is able to create NGACs, and as nominal power increases more NGACs are created) and once sufficient certificates have been created selling the excess ones. Since the profit earned with the carbon tax scheme is considerably higher, the curve associated with this scheme has a steeper slope and in high nominal powers leads to greater NPW values.

Variation of NPW as a function of CHP system nominal power for OWC mode of operation is depicted in Fig. 5. Maximum NPW values are provided by nominal powers of 6300 kW for the carbon tax scheme and 5900 kW under ETS. The payback periods are 6.3 years and 8.3 years, respectively. As shown, the optimum nominal power and NPW values are less than that of TWC mode due to the fact that selling the excess produced electricity in OWC mode is not possible while with TWC operational mode, the

system sells electricity to the grid for the nominal powers of above 5440 kW (there is no surplus electricity for the nominal powers of 5440 kW and less, therefore NPW values are the same for both modes of operation).

We note that, even though in OWC mode selling surplus electricity to the grid is not possible, for some months the most economically favourable nominal powers noted above are greater than the electricity demand and therefore, considering the base load operational strategy, there is some excess electricity in those months. This is due to the fact that we purposefully didn't impose the technical constraint associated with this mode to compare the optimum nominal powers with the maximum possible one (5440 kW). If the maximum possible nominal power is less than the optimum one (which is the case here), the inevitable consequence is to choose the maximum possible capacity which adversely affects the economics of the system. Working in partial load conditions could address this issue [see the off-design analysis methodology and its application provided by Aghaei Meybodi and Behnia (2011)]; hence, manufacturers play a crucial role in promoting utilisation of Stirling engines in on-site power generation systems.

In estimating NPW values for the considered range of nominal powers, the assumption is made that the mine produces enough methane to provide fuel for the system. However, the maximum possible nominal power of the CHP system in order to be continuously supplied by CMM (considering monthly available methane) for both operational modes and under both schemes is 4500 kW (the highlighted points on the graphs). Consequently, in spite of not being the optimum option, the selected nominal power of the Stirling engine-based CHP system is 4500 kW (i.e. three 1.5 MW engines) with the payback periods of 11.5 years and 14 years for the carbon tax scheme and ETS, respectively.

Fig. 6 shows the operational strategy of the selected prime movers of the Stirling engine-based CHP system. As noted before, prime movers work at their nominal capacity throughout the year. The studied CHP system is very effective and supplies 70.6% of the annual electricity demand as well as 62.2% of the annual thermal requirements. Further, a substantial reduction in greenhouse gas emissions can be achieved by incorporating the CHP system at the mine. Fig. 7 compares the monthly amount of mine emissions before utilising the CHP system (methane emissions) and after installing the system (the total emissions including unused methane emissions as well as emissions as a result of fuel combustion in the engine and the dryer). The results indicate that incorporating the Stirling engine-based CHP system leads to a 65.4% decrease in annual greenhouse gas emissions.

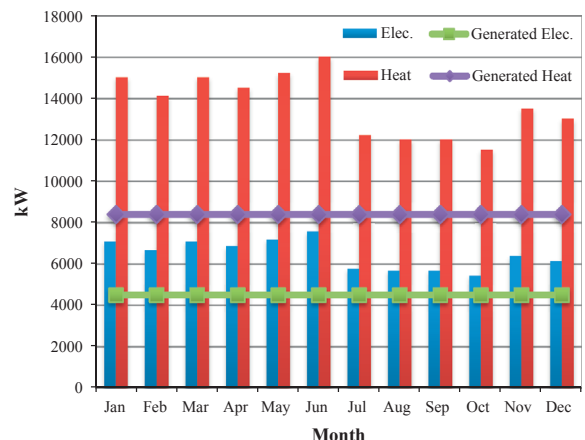


Fig. 6. Operational strategy of the selected prime movers.

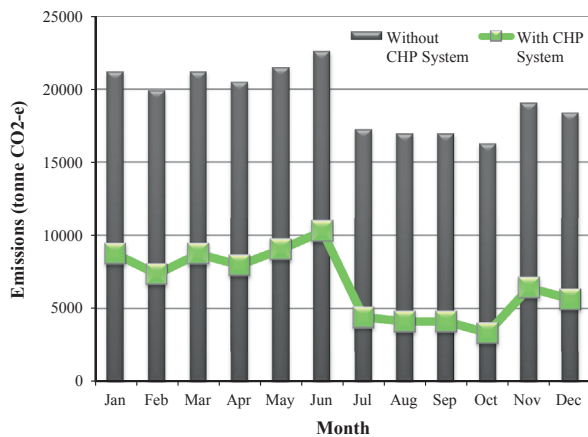


Fig. 7. Monthly greenhouse gas emissions.

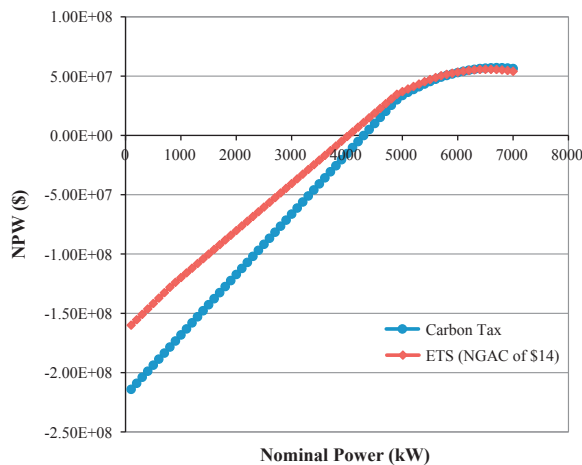


Fig. 8. Variation of NPW versus CHP system nominal power in TWC mode of operation.

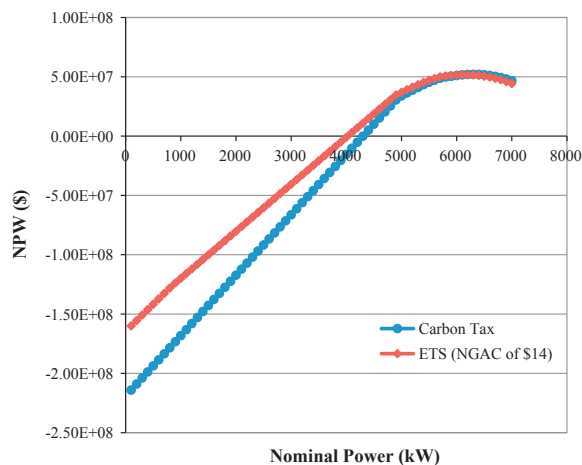


Fig. 9. Variation of NPW versus CHP system nominal power in OWC mode of operation.

In summary, our analysis leads to the conclusion that incorporating the modelled CHP system at the coal mine not only substantially reduces the greenhouse gas emissions, but also the system is economically favourable. Moreover, due to the significant economic burden, the carbon tax scheme creates a great incentive for the coal mining industry to address the greenhouse gas emissions. To examine this further, NPW values under ETS are recalculated considering a new NGAC price, \$14, which is the

maximum spot price in the implementation period of the scheme (reached in 2006). Figs. 8 and 9 show the variation of NPW as a function of CHP system nominal power under both environmental policies and for TWC and OWC modes of operation. This price results in higher NPW values (except for the capacities below 600 kW) in comparison with the nominal NGAC price and ETS is more economical than the carbon tax scheme for a broader range of nominal powers (nominal powers below 6100 kW). However, similar to the nominal case, under the carbon tax scheme economic burden when methane emissions are high is considerably larger.

6. The potential of Stirling engine-based CHP systems in Australia

As previously noted, due to the abundant coal reserves, the Australian economy and power generation sector considerably rely on coal. In 2009, coal made up 39% of the country's fuel consumption followed by petroleum products (34.4%) and natural gas (21.4%). Further, the majority of Australia's electricity is produced using black and brown coal, which accounted for 76.7% of the total electricity generation in 2008–2009 (Department of Resources, Energy, and Tourism, 2011).

In Australia, there are seven coal mine methane fuelled grid connected power stations with the total generation capacity of 215 MW and emissions reduction of 6.5 Mt CO₂-e (Department of Resources, Energy, and Tourism, 2010). However, it is estimated that in 2010 the methane emissions from the Australian coal mines reached almost 29 Mt CO₂-e (Department of Climate Change and Energy Efficiency, 2012). This highlights the high potential of application of power generation systems that operate on coal mine gas as currently a substantial amount of viable fuel is being wasted. In addition, none of these power generation systems utilize the Stirling engine as the prime mover which, due to its previously noted advantages over conventional prime movers, proves to be appropriate for coal mine gas applications.

To examine the impact of variations in the considered environmental policies on the economic viability of the modelled system, we have conducted a sensitivity analysis. Figs. 10 and 11 show the variation of NPW values due to a $\pm 25\%$ change in nominal carbon tax rate and Figs. 12 and 13 illustrate changes of NPW values as a result $\pm 25\%$ change in nominal NGAC price for TWC and OWC modes, respectively. As noted before, NPW values associated with the two operational modes are the same for the nominal powers of 5440 kW and lower (under both schemes) and as is evident from the figures, after 5440 kW the values are slightly different while the trend is almost the same. With the carbon tax scheme, as Figs. 10 and 11

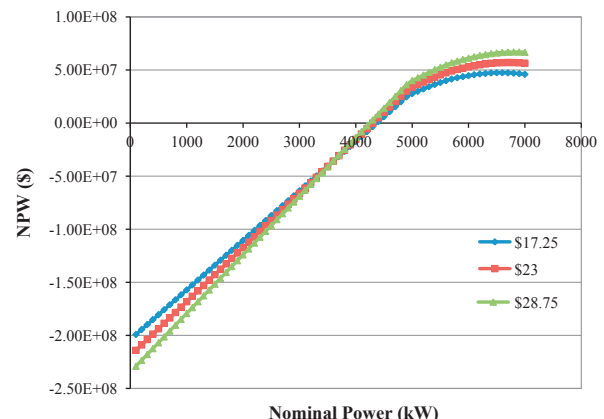


Fig. 10. Variation of NPW values as a function of carbon tax rate in TWC mode of operation.

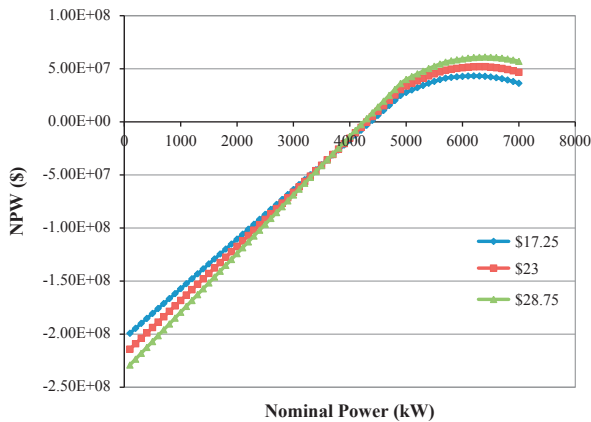


Fig. 11. Variation of NPW values as a function of carbon tax rate in OWC mode of operation.

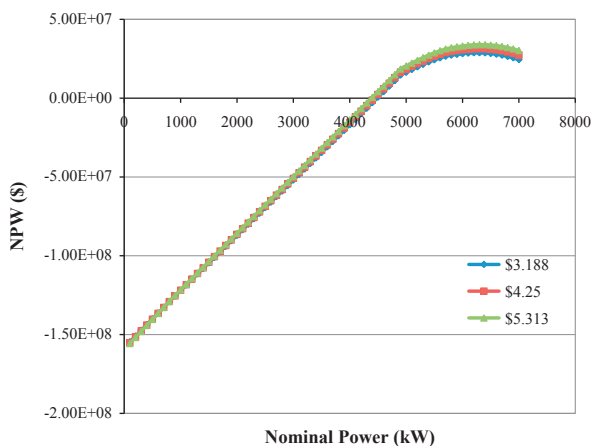


Fig. 12. Variation of NPW values as a function of NGAC price in TWC mode of operation.

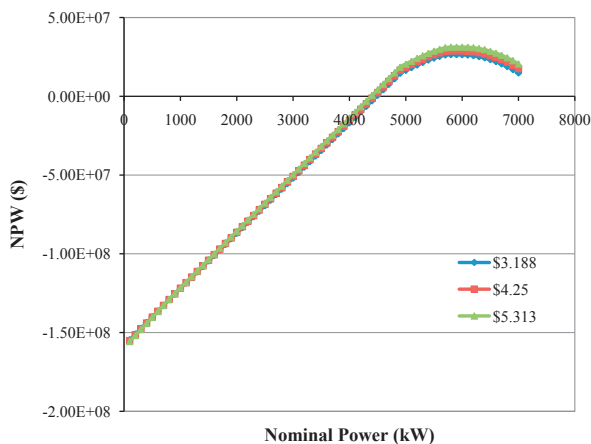


Fig. 13. Variation of NPW values as a function of NGAC price in OWC mode of operation.

show, a higher tax rate leads to lower NPW values for low CHP system nominal powers and as nominal power increase, NPW values related to the higher rate rise with a steeper slope. This behaviour is consistent with the significant economic impact of carbon tax on the system which was previously discussed.

Under the ETS policy, similar to the carbon tax scheme, greater NGAC prices result in lower NPW values for low nominal power

(as the CHP system does not create sufficient NGACs and has to buy some certificates from the market), but as nominal power rises and system begins to sell certificates, higher NGAC prices lead to larger NPW values. However, unlike the carbon tax scheme NPW values are extremely close, particularly for low nominal powers. This provides clear evidence that the economics of the CHP system is more sensitive to the variation of carbon tax rate than changes in NGAC price.

For the purpose of comparison, it is noted that under ETS, a 25% increase in NGAC price leads to a payback period of 13.4 years (a 4.3% decrease) for the selected CHP system (nominal capacity of 4500 kW, with the payback period of 14 years). Further, the payback period increases by 5% (to 14.7 years) if the price declines by 25%. The percentage of change with variation of carbon tax rate is more than twice as high; a 25% rise in the nominal carbon tax rate reduces the payback period of the selected system (i.e. 11.5 years) by 9.6% (to 10.4 years) and a 25% decrease in the tax rate results in a payback period of 12.7 years (a 10.4% rise).

7. Concluding remarks

To conduct an optimization-based feasibility study on the application of Stirling engines in coal mine CHP systems, we have developed a techno-economic approach based on the net present worth analysis. Two modes of operation are considered; namely, OWC mode and TWC mode. Further, to clarify the extent to which the economics of the system is affected by environmental policies, the two commonly adopted schemes (i.e. a carbon tax and emissions trading) are considered and by conducting a sensitivity analysis their economic impact is studied.

For demonstration purposes an Australian coal mine was considered as the case study. The results indicated that incorporating a Stirling-engine based CHP system leads to a substantial reduction in greenhouse gas emissions. In addition, a significant proportion of electricity and heat demand is generated on-site and the CHP system is proven to be economical. It was further observed that the economic burden of the carbon tax scheme is larger than that of emissions trading scheme and consequently a carbon tax may provide a greater incentive for coal mine industry to address the methane emissions.

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